12-2008

The Effect of Distributed Generation on Distribution System Reliability

Nura Nubee Sabir
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Nura Nubee Sabir entitled "The Effect of Distributed Generation on Distribution System Reliability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Fangxing Li, Major Professor

We have read this thesis and recommend its acceptance:

Leon Tolbert, Kevin Tomsovic

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To Graduate Council:

I am submitting herewith a thesis written by Nura Nubee Sabir entitled "The Effect of Distributed Generation on Distribution System Reliability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Electrical Engineering.

Dr. Fangxing "Fran" Li

Major Professor

We have read this thesis
and recommend acceptance:

Dr. Leon Tolbert

Dr. Kevin Tomsovic

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

The Effect of Distributed Generation on Distribution System Reliability

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Nura Nubee Sabir
December 2008

ACKNOWLEDGEMENTS

All praises are due to the creator with whom all things are possible.

To my parents, Taalib-Din and Safiyyah Sabir, much love, respect and admiration. May you forever have internal peace.

To all of my brother and sister, whom I love dearly, and so fortunate to have in my life: Syid, Dawn, Muna, Suni, Tacara, Ismail, Tiaria, Dalyah, Kaamilyah, Shah, Zahrah. And to my two nephews: Hakeem and Jalil and beautiful niece: Aaliyah. My family keeps me grounded and focused on what is important in life.

A special thanks goes out to Mr. Pippin, who relentlessly worked on my behalf. Thanks for all your efforts. May the creator continue to shower blessings your way.

I want to acknowledge The National Consortium for Graduate Degrees for Minorities in Engineering and Science, Inc (GEM) and Pipeline Engineering Diversity Program funded by the Department of Energy, who made it possible for me to

To my committee, Dr. Tomosovic and Dr. Tolbert. I appreciate all your time and efforts.

Last but certain not least, I want to give a big thanks to my Adviser, Dr. Fangxing Li, who went over and beyond the call of duty. I will forever be grateful.

ABSTRACT

Electricity produced and delivered to customers constitutes one of the largest consumer markets in the world. As a nation we have become so dependent that most daily functions would be suspended if there were any interruption in power generation, transmission and distribution. Historically there has been a great deal of effort put into modeling and improving the reliability of the generation and transmission systems. However, when compared to the generation and transmission systems, considerable less resources has been placed on the details of making the distribution system more reliable. Majority of all interruptions experienced by the customer in a given year are due to the distribution system. In addition, since the penetration of distributed generation is projected to increase to at least 20% of peak load by 2020, the inclusion of distributed generation in distribution system reliability assessment is highly desired.

This research seeks to model the impact of distributed generation to distribution system reliability. Since utility-connected distributed generation is typically installed close to the consumers, it can reduce the current at the main feeder. Consequently, it increases the chance that a stressed feeder can be reconfigured under a fault at a neighboring feeder. As a comparison, it may be impossible to reconfigure feeder connection because reconfiguration will lead to line overflow without distributed generators to supply part of the load.

The reliability assessment in this work is carried out with analytical approach and sequential Monte Carlo simulation. The analytical approach presents the reliability measures like SAIFI and SAIDI during the course of an average year. Hence, the mean values of SAIFI and SAIDI for distribution systems with or without distributed generation are obtained. However, sequential Monte Carlo simulation can give the probabilistic distribution of SAIFI and SAIDI based on a large sample of random failures of system components. Test results from a system modified from the IEEE 34-bus system will be presented based on the analytical approach and the Monte Carlo simulation. It is shown that installation of distributed generators can improve the distribution system reliability considerably.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1

Introduction

1.1. Distribution System

The electric market represents one of the largest consumer markets in the world. In the United States alone the electricity sales make up a little over 3% of the total gross of domestic products. When we fragment the sales of electricity, 50% is fuel, 20% is generation, 5% is transmission, and 25% is distribution[1]. Not only does electricity play a large role in our economy but also it has a tremendous impact on the consumer's lifestyle. As a nation we have became so dependent that most daily functions would be suspended if there were any interruption in the delivery of this power. A typical power system is divided into three distinct yet cohesive systems: generation, transmission, and distribution systems. The generation system is responsible for production of the power. Through an electromechanical energy conversion process traditionally stimulated by nuclear power, hydropower, or fossil fuels voltage ranging from 11kV to 30kV is generated. The voltage is then stepped up by a power transformer in preparation for transportation long distances through the transmission system; the voltage range is between 69kV to 1100kV, where the typically voltages in the United States is 69kV, 115kV, 138kV, 161kV, 230kV, 500kV, 765kV, and 1100kV [1]. The power is then stepped down for the distribution system. The distribution system is responsible for delivering the power directly to the consumer. The distribution system is furthered divided into sub-parts: distribution substation, primary distribution systems, distribution transformers, and secondary distribution systems. The distribution substation is where the high voltage is terminated and stepped down to primary distribution levels, ranging from 4.16kV to 34.5kV; typically 12.47 and 13.8kV [1]. Figure 1.1 shows a one-line diagram of a distribution substation.

As the power enters the substation from the transmission line there is a disconnect switch which is capable of totally separating the transmission system from the distribution system. Notice the various components (i.e. voltage transformer, current transformer, power transformer, lines) that make up the substation are in a radial topology; this will become exceedingly important in later discussion. The power is stepped down to primary distribution levels of 4.16kV to 34.5kV and exits the substation through feeders. Figure 1.2 shows a one-line diagram for a typical primary distribution system. The feeders are routed through out a particular service territory. Each feeder has a main trunk and extending from the main trunk is lateral taps that are more intricately routed through out the service territory to ensure power is capable of reaching all customers [1]. The lateral taps can have a direct connection the main trunk; however, various types of protection components such as sectionalizers, fuses, or circuit breakers usually connect it.

Lastly, prior to the power being delivered directly to the customer it flows through the secondary distribution system where the power is stepped down to levels ranging between 5kW and 2500kW [1].

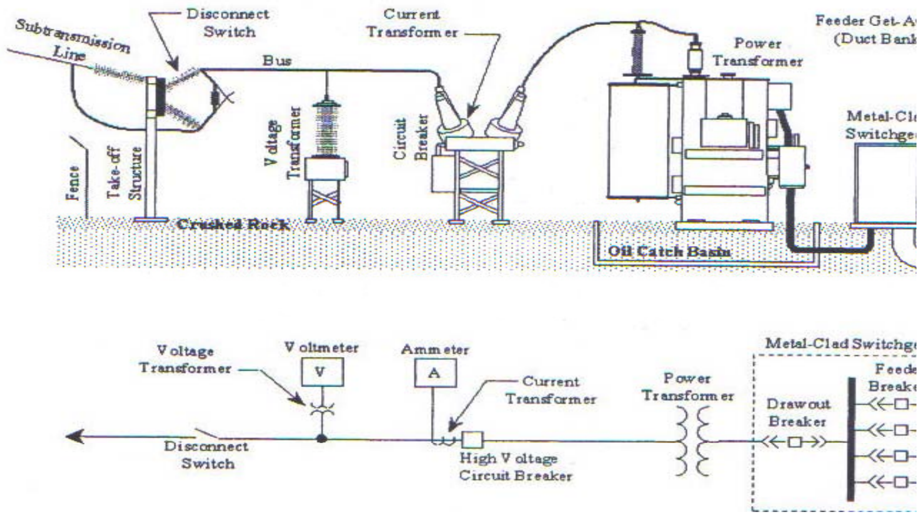

Figure 1.1 Distribution Substation elevation and single-line diagram

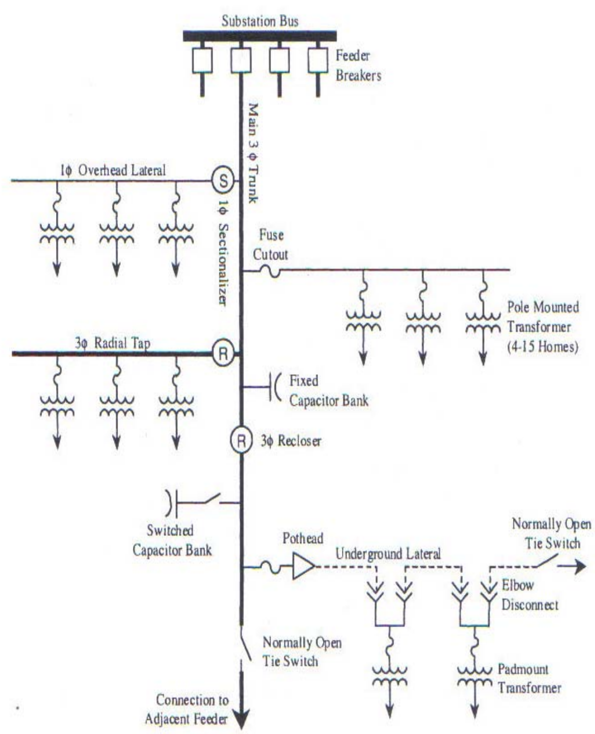

Figure 1.2 Primary Distribution System one-line diagram

1.1.1. *Distribution System Operation*

Distribution system operation is comprised of the dispatch centers, operators, and crew. The dispatch centers are ran by operators who engage in real-time control and operation using Supervisory Control and Data Acquisition (SCADA). SCADA offers the ability to monitor such things as feeder loading or equipment trouble, which is sounded by a device alarm or by customer's interruptions [1]. When there is a contingency (fault) in the system operator can either perform a remote reconfiguration or send a crew to perform corrective measures such as a switching action or repairing damaged equipment. The crew is also responsible for performing routine maintenance. All equipment requires inspections, testing and maintenance to ensure proper operations and to minimize probability of failure.

1.1.2. *Distribution Reliability*

Reliability as defined by IEEE is the ability of a system to perform its required function under normal condition for a specified amount of time. When this definition is applied to the distribution system we concentrate on individual components and their ability to operate under normal conditions and how their operation affects the customer. In order to quantify the reliability of the distribution system metrics known as reliability indices are used. The indices are statistical collections of reliability data, they are used as way to assess the effectiveness the distribution system to supply power to the customer continually [1, 2]. Reliability indices can be placed in two categories, local indices and global or system indices. Local indices measure the impact to the individual customer where global indices measure the overall reliability of the system [3]. The most commonly used global indices are those that represent sustained interruptions; System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI)[2, 4, 32]. SAIFI indicates how often an average customer experiences an interruption for a specific amount of time [5]. The formula for SAIFI is

$$SAIFI = \frac{\sum Total\ Number\ of\ Customer\ Interrupted}{Total\ Number\ of\ Customers\ Served} \tag{1.1}$$

SAIDI indicates the time-span of the interruption for the average customer during a specified amount of time [5]. The formula for SAIDI is

$$SAIDI = \frac{\sum Customer\ Interrupted\ Duration}{Total\ Number\ of\ Customers\ Served} \tag{1.2}$$

There are other indices such as customer average interruption duration index (CAIDI), which represents the average time required to restore service. The formula for CAIDI is

$$CAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Customers\ Interrupted} \tag{1.3}$$

Average service availability index (ASAI), ASAI represents the fraction of time (often in percentage) that a customer has received power during the defined reporting period. The formula for ASAI is

$$ASAI = \frac{\sum Customer\ Hours\ Service\ Availabilty}{Customer\ Hours\ Service\ Demands} \tag{1.4}$$

The aforementioned indices are for sustained interruption, there are also other indices for outages that are momentary; Momentary average interruption frequency index (MAIFI) indicates the average frequency of momentary interruptions and the formula is given as:

$$MAIFI = \frac{\sum Total\ Number\ of\ Customer\ Momentary\ Interruptions}{Total\ Number\ of\ Customers\ Served} \tag{1.5}$$

Also, Momentary Event Average Interruption Frequency Index ($MAIFI_E$) indicates the average frequency of momentary interruption events and its formula is:

$$MAIFI_E = \frac{\sum Total\ Number\ of\ Customer\ Momentary\ Interruptions\ Events}{Total\ Number\ of\ Customers\ Served} \tag{1.6}$$

However this thesis will cover only SAIFI and SAIDI. In order to perform these calculations each component needs to be assigned reliability data [2]. The three basic parameters that define the reliability data for each component are: average failure rate λ, average outages duration *r*, and annual outage duration *U* [6]. This data that is used to assist with the computation of these indices ideally should be supplied by the utilities' historical outage data, however most utilities do not have such data available in the detail needed to perform calculations [2, 3]. Therefore there is a stochastic Monte Carlo method used to predict the needed data, which will be discussed in detail later.

1.2. Distribution Reliability Assessment

There are two methods in which distribution reliability is normally assessed: analytical and by simulations. The analytical method use estimations and assumption for the systems outage record and the reliability results produced are average values [3, 6]. Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling to compute results. Monte Carlo methods tend to be used when it is infeasible or impossible to compute an exact result with a deterministic algorithm. The basic Monte Carlo methods are sequential and non-sequential. Both the analytical and Monte Carlo Sequential Simulation Technique will be discussed later in detail.

1.3. Distributed Generation

Distribution systems initially were designed with no generation capabilities; there was a single source with a radial configuration [7, 8]. However with congressional mandates for deregulation, generation units have been introduced to the distribution system [8]. Distributed Generation (DG) are units of limited size that are connected directly to the distribution network or on the customer site [7, 8]. Typically the units used are gas turbines powered by synchronous generators, wind powered induction generators, fuel cells, hydro, and photovoltaic [7, 9]. They offer various applications as well various benefits. Three more common applications include backup generation, peak shaving, and net metering [7]. While the benefits include voltage support, energy-loss reduction, release of system capacity and improvement in reliability [8, 10]. This research seeks to explore how distributed generation will affect reliability.

CHAPTER 2

Literature Review

2.1. Reliability assessments

As stated previously, reliability is the expectation that a given system will perform its intended function given normal operation conditions for a specific amount of time. The topic of reliability and its relation to the power system is not new and research in the area continues to grow every year. As the demand from customers for more secure, adequate, and cheaper power increases, as deregulation policies are enforced, and as reliability standards are developed, reliability in the power system remains a hot topic [2-4, 11]. Reliability assessment addresses the need to quantify the quality and availability of power for each customer by predicting the interruption profile of a given distribution system in relations to the system's specific topology and reliability data [2, 6]. Reliability assessment methods are divided into two areas, analytical and simulations [2, 12-15]. There have been attempts to combine both methods [12, 15].

2.1.1. *Analytical Method*

The analytical method uses mathematical solutions to evaluate mathematical models; this technique has been used for many years. In this approach, the impact to all load points due to each component failure will be considered as well as the average failure rate of the component. Then, the interruption frequency and duration at each load point is calculated to eventually calculate the system reliability indices such as SAIFI and SAIDI [1, 30-31].

When calculations are performed the mean values are the results produced and they represent the reliability indices, which prove to be very useful however that does not give a realistic picture. The reliability indices are in fact variable [16]; therefore it is beneficial to be able to look at its distribution. The probability distribution offers a way for the variations in the reliability indices to be shown, therefore Monte Carlo simulation is a more popular choice [14]. Although very time and computationally intensive, the simulation method offers more flexible, practical results [3, 6, 12]. There has been a considerable amount of work done using the Monte Carlo simulation [8, 14, 15, 17, 18, 30]. Monte Carlo estimates the indices by simulating the actual process and random behavior of the system [18].

2.1.2. *Monte Carlo Simulation Method*

Again the Monte Carlo simulation is of two categories: non-sequential and sequential, which both have its advantages and disadvantages associated [8, 14, 15, 17, 18]. Since probability distributions has the ability to show the likely range of the reliability indices, the sequential method is the preferred choice, while it is rarely achievable with the non-sequential method [18]. The sequential simulation method has the ability to model operating characteristics and contingences for a given system chronologically, an up down cycle is created for each component in the system that is representative of its current state [18, 19]. For this reason the sequential method is also referred to as the state-duration sampling method. And the non-sequential method is referred to as the state sampling method due to the fact that sampling of the state of each component is random and a non-chronological system state is found [15, 19]. The sequential is also preferable because the load, which is variable, can also be successfully modeled [19]. The validity of the simulated results depends heavily on the load, therefore a detailed custom load profiles is needed for each individual load points [12]. Load profiles can be significantly different for the various types of customers: residential, commercial, industrial, etc. Reference [12] offers an alternative way to model the individual customer load characteristics by combining them with the annual peak load.

As mentioned earlier there are three basic parameters that define the reliability data for each component: average failure rate λ, average outages duration r, and annual outage duration U [6]. These parameters are essential to producing realistic and valid results. Both averages values and probability distribution have been used, however average values fail to reflect the reliability of a component entirely leaving margin for overestimating the reliability of a customer that is actually experiencing adverse conditions [14, 20]. But failure rate has traditionally been represented as a constant and still offers good assumptions if the computing the annual reliability behavior [4]. After determining and weighting the impact of failures on a given system for all customers, the reliability assessment is then complete [4].

2.2. System Reliability and Load Point Reliability Indices

We have previously mentioned the reliability indices SAIFI, SAIDI, CAIDI, ASAI, MAIFI (or $MAIFI_{E)}$; these indices are known as the system reliability indices. This distinction is being made because these indices are determined by the failure of each individual component and the duration of the failure for a given year, but we also have load point reliability indices. For load point reliability indices the number of failures and how long those failure occurs is taken from each load point opposed to the individual components. Load point reliability indices are the failure rate, the repair rate, and the average load annual outage time. These indices can be evaluated using the following formulas:

$$\lambda_i = \sum \lambda \qquad (2.1)$$

$$r_k = \frac{\sum \lambda_i r_i}{\sum \lambda_i} \qquad (2.2)$$

$$U_k = \lambda_k r_k \qquad (2.3)$$

Where λ_i=failure rate of component *i*
λ_k=failure rate of load point k
r_i=outage time of component *i*
r_k=outage time of load point *k*
U_k=average annual outage time of load point *k*

Load based reliability indices will not be covered in this research. However it is notable to mention from load point indices system indices SAIDI, SAIFI, CAIDI, and ASAI can be computed using the following formulas:

$$SAIFI = \frac{\sum \lambda_k N_k}{\sum N_k} \qquad (2.4)$$

$$SAIDI = \frac{\sum U_k N_k}{\sum N_k} \qquad (2.5)$$

$$CAIDI = \frac{SAIDI}{SAIFI} \qquad (2.6)$$

$$ASAI = \frac{1 - \sum U_k N_k}{\sum N_k \times 8760} \qquad (2.7)$$

Where N_k=number of customers at load point k.

Again it should be noted that this work will address the system reliability indices SAIFI and SAIDI

2.3. Impact of Distributed Generation

Distributed Generation has the potential to be an economical solution to load growth, capacity, and reliability issues within the distribution system [10, 21]. The impact of DG on reliability is a topic that has received considerable interest [22]. There has been a great deal of research that concentrates on how to integrate DG into the power systems [23-26]. Interconnecting DG to the distribution system has resulted in some undesirable phenomena such as harmonic contamination, transient/small signal stability, and quality control [26], however reference [26] and [27] has explored ways to minimize these issues. Therefore this thesis will neglect any interconnections concerns and assume that the DG is fully functional. As DG is assumed to offer an increase in reliability there has been papers devoted to including the DG in the planning and design phase [22, 28].

CHAPTER 3

Reliability Assessment with Distributed Generation

3.1. Distributed Generation

Research has predicted that in the next several years distributed generation may account for up to 20% of all new generation [29]. As previously mentioned DG offers the opportunity for the reliability of a given distribution system to be improved. In addition, DG increases the chance that a stressed feeder can be reconfigured under a fault at a neighboring feeder [7]. It may be impossible to reconfigure feeder connection because reconfiguration will lead to line overflow without distributed generators to supply part of the load.

3.1.1. *Distributed Generator Size*

Again distributed generators are of limited size; typically they range from several kilowatts to ten megawatts [7, 10]. However with the growth of the photovoltaic programs and building of wind power farms, 100 MVA or less distributed generators can be connected directly to the distribution system or on the customer site [8].

3.1.2. *Distributed Generator Application*

While DG has various applications as it applies to the distribution system, such as net metering and peak shaving, its use as a backup generation is considered. When there is an interruption, distributed generators are started and supplied to appropriate loads, especially sensitive and critical loads. In this case, since the distributed generators are used as backups, they are not operational. So when there is a need for them, there is an associated startup time, which varies. However, for critical loads the use of power electronics can result in an uninterruptible supply of power [7]. The startup time of the DG definitely affects the reliability index SAIDI. While this is a real issue and real concern, we will assume that connection is instantaneous, neglecting any startup time.

.

3.1.3. *Distributed Generator Operation*

There is a couple of ways to operate DG depending on its application. For instance for peak shaving, during normal operation the DG is connected to system, during an outage on the distribution system the DG is disconnected. There is also island mode, again the DG is connected to the system and during a fault remains in service if it is connected to a segment that is not affected; the DG must be able to support line capacity. Also as an application of peak shaving, when an interruption is experienced the DG is disconnected, the system is reconfigured and indirectly affected customers are switched to an adjacent circuit, the DG is switched to the same adjacent circuit and re-energize. In these three cases, the operations are for peak shaving or even net metering; however this research focuses on the application of back up generation solely. Therefore, it will operate similar to the island mode with the exception that it is not normally connected to the system during normal operations; it is only after a contingency that it is connected.

3.1.4. *Distributed Generator Placement*

The placement of the DG has a direct effect on the reliability. There will be no significant improvement by inserting DG into a segment of a circuit that experience outages often. In order to find an optimal location, DG is inserted in a segment, a reliability assessment is performed, and then the DG is move to another segment and a reliability assessment is performed, this process is continued until all predetermined segments are checked [21]. Thus the area that proves to provide the greatest improvement in reliability is chose and the DG placement area.

The optimal placement of DG is a separate topic which can be very complicate involving non-linear, discrete optimization technique in theory. In reality, DG placement may be affected by many non-technical issues such as the geographic, construction constraints. So, this work simply assumes the DG placement is given. The test system in Figure 3.1 has four segments that are prime candidates for DG placement, two segments for each circuit. Instead of using only two DG and finding the optimal location between the two segments, four DG were placed in each segment.

In the effort to quantify the impact that DG will have a reliability assessment in this work that will be carried out with an analytical approach and sequential Monte Carlo simulation.

3.2. Distribution system model

The first step in performing the reliability assessment of the distribution system is to develop a model in which to perform appropriate calculations. MATLAB version

7.0.0.19920 (R14) was used to develop algorithm and to perform all calculations. Figure 3.1 shows the test system that was modeled. IEEE 34 node system was duplicated and tied together using a normally open switch. This configuration allows for each individual system or circuit to serve as a backup source if needed, which would potentially improve reliability.

Each system has a total of two automatically controlled distributed generators connected by a normally open switch; this will be looked at closely later. The test system is sufficiently small to permit the execution of reliability calculations with reasonable computation time but attempts to have enough detail to represent a practical system. The system supplies different combinations of time varying loads. The test system has 16 load points and each load point has a different load curve with an associated peak load value and average load value. Load profiles vary from hour to hour, from day to day, from year to year, and from season to season. In addition to the load curve that is assigned to each load point there is a certain amount of customers that are assigned. For customers it assumed that their load varies from approximately 5 KVA to 10KVA. Based on the average value at the load point the number of customer was determined by assigning each customer an average 8KVA load. The load curves that were used for both the analytical method and the Monte Carlo Simulation method are shown in Figure 3.2. For the analytical method the average value of the load was taken as documented in Table 3.1. The MATLAB program that was developed specifically works with this test system, however with some modification to the algorithm, the program can be used to analyze other radial distribution system with similar topology.

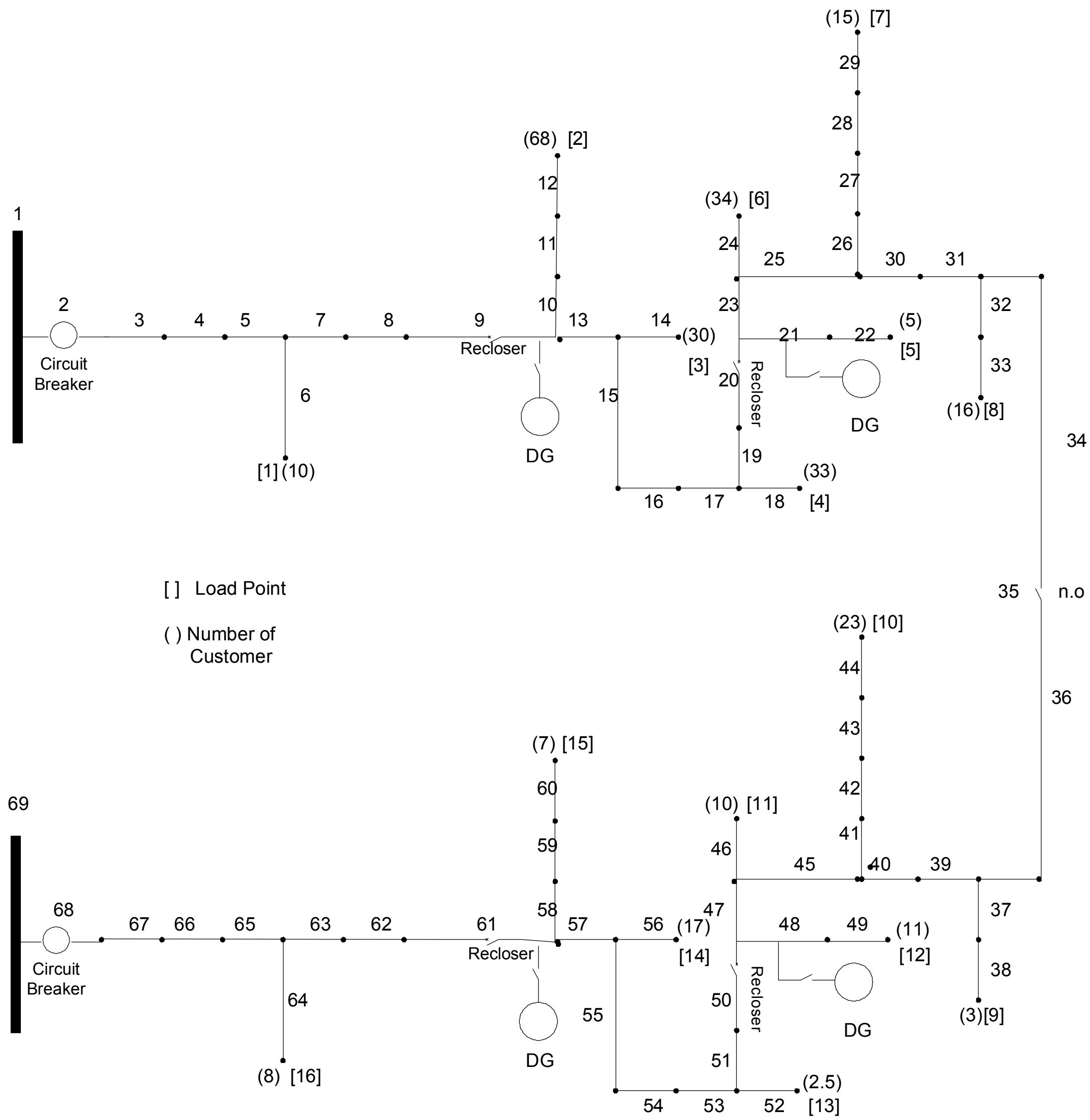

Figure 3.1 Test System Modified from the IEEE 34-node Test System

Table 3.1 Peak value, average value, and customer class of each load point

Load Point	**Peak Load (KVA)**	**Average Load (KVA)**	**Number of Customers**
1	145.7	81.02	10
2	893	543.97	68
3	505	242.61	30
4	569	260.33	33
5	72.85	40.51	5
6	446.5	271.98	34
7	252.5	121.31	15
8	284.5	130.17	16
9	48.57	27.01	3
10	297.67	181.32	23
11	168.33	80.87	10
12	189.67	86.78	11
13	36.43	20.26	3
14	223.25	135.99	17
15	126.25	60.65	7
16	142.25	65.08	8

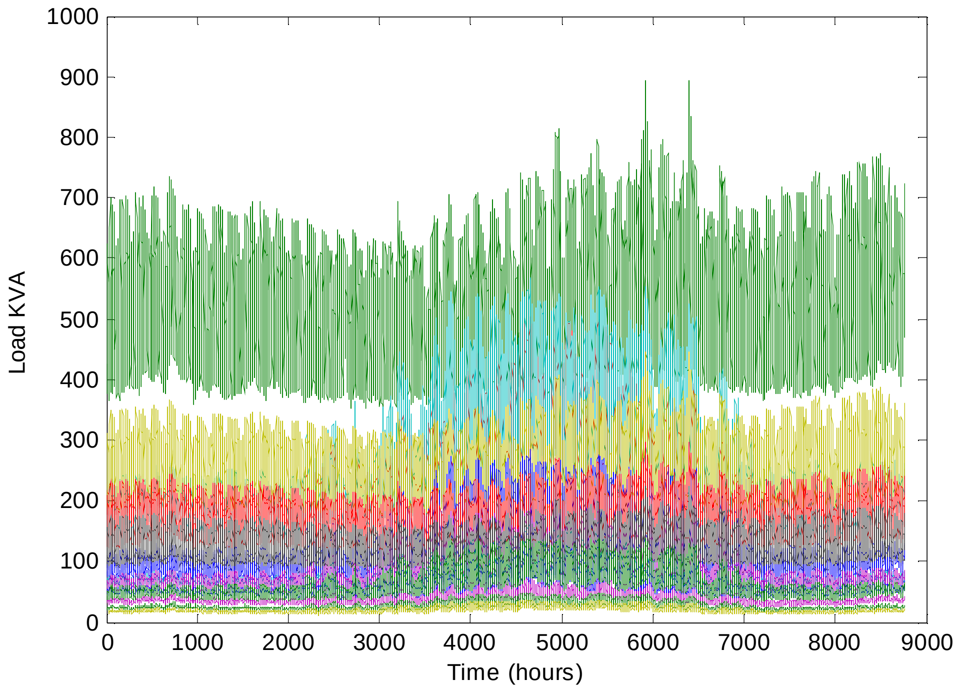

Figure 3.2 Load Curves for 16 Load Points on Test System

3.2.1. *Component Modeling*

Modeling of a distributions system begins with identifying the unique characteristics of the various components that is used as building blocks to create a variety of distribution system configurations. The parameters that describe the characteristics of each component need to capture all requirements critical to the systems reliability while remaining as simple as possible. The two parameters that are used in this model are the failure rate and mean time to repair (MTTR). This reliability data is of extreme importance to the overall reliability assessment, without good data the results are baseless and without merit.

The failure rate describes the number of times per year that a particular component will experience a sustained interruption. A commonly used graphical representation of the failure rate to show the variation with time is the Bathtub curve [1]. The bathtub curve describes the nature of each component beginning with the initial installation to when it is decommissioned. In theory, each component will go through three stages in its life: the infant mortality period or the break-in period, useful life, and the wear-out period. During the break-in period there is typically a relatively high failure rate for various reasons including but not limited to incorrect installation, manufacturer defects, and damage during shipping and handling. Once the component leaves the break-in, considering the component actually makes it through, it enters the useful life period. The period is characterized by relatively low constant failure rate. Although using the bathtub curve definitely has it advantage for making the model more realistic, this research will use a constant value to represent the majority of the lift time of each component.

The MTTR is the average or expected repair time, which describes the amount of time in hours it takes for a particular component to be repaired after a failure has occurred. Table 3.2 shows the range of the failure rates and MTTR values used for the model based on Reference [1]. The test system is comprised of primary trunks, disconnect switches (sectionalizers), reclosers, and transformers. The disconnect switches and reclosers will be assumed to be fully operational at all times, hence failure rate and MTTR is reflected as zero. The actual data used for failure rate and MTTR can be found in the MATLAB code in the Appendix.

Table 3.2 Reliability of overhead distribution components

Description	λ(per year)			MTTR(per hour)		
	Low	Typical	High	Low	Typical	High
Primary Trunk	0.02	0.100	0.300	2.0	4.0	8.0
Lateral Tap	0.02	0.16	0.300	2.0	4.0	8.0
Disconnect Switch	0	0	0	0	0	0
Line Recloser	0	0	0	0	0	0
Transformer	0.004	0.010	0.015	3	5	10

3.2.2. *System Modeling*

After successful characterization of each component in a given system, modeling the behavior of the entire distribution is needed. As we begin to study the behavior of the distribution system it is beneficial to view the system in terms of state spaces. Either the system is in an operational state meaning that no protection devices (sectionalizers, reclosers, or fuses) are tripped, all components are fully functional, any switches are in their initial positions, and loading levels are within source capacity levels; or the system is in any other state, meaning that there has been some modification to the initial settings due to some disturbance in the system usually due to a fault, a malfunction of a component or even scheduled maintenance. Predicting the outages and interruptions and noting the system's response to those outages and interruptions is an essential part of reliability modeling. By identifying the events that will cause the system to operate in a state that is not normal or fully operational and then quantifying the effect it will have on the customer is the key to the reliability assessment.

3.2.3. *Radial System Structure*

A radial system is defined as a system where each component has a unique path to a source of energy. Each component establishes a well-defined relationship with the components on its adjacent sides, which will be referred to as the parent/child relationship. The component that is located downstream of a given component is referred to as the child, while the component that is located upstream of a given component is references as the parent. The direction of power in a radial system is always known, it flows away from the source. Therefore power flow calculations are easily preformed. Navigation through the radial system identifying source of power, protection devices, fault isolations point, affected customers, and switches for customer restoration is of great importance when performing reliability analysis. After a contingency occurs there are a series of events that take place to minimize impact to entire system. These events include but are not limited to isolation of effected area by predetermined switching schemes and possible restoration of power to as many customers as possible. Typically upstream and downstream searches are performed; given a component starting point, a trace of subsequent parent or child is executed until a pre-determined stopping criterion is reached flagging successive components along the way as shown in Figure 3.3. For example in Figure 3.4, the whole segment or region should be automatically isolated

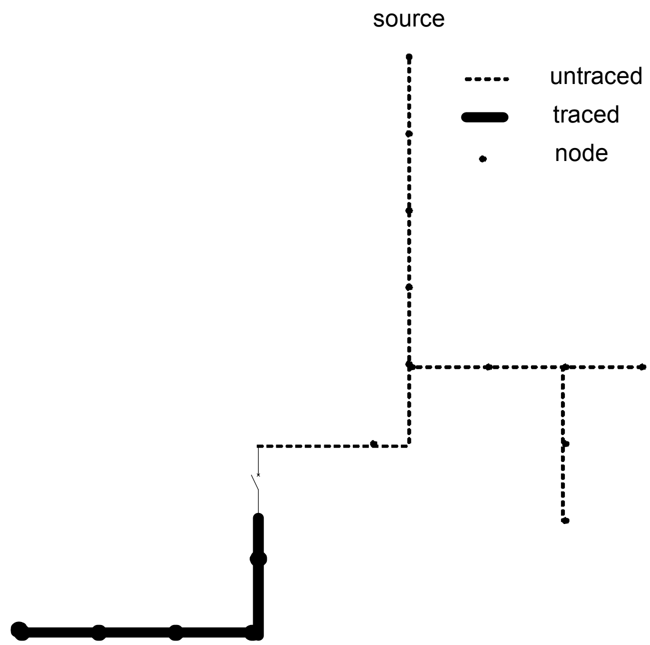

Figure 3.3 Downstream Search

without performing a search either downstream or upstream. Comparing Figure 3.3 and 3.4, identifying the affected region was achieved in five steps and one step, respectively. This saves on computation time, and proves to a benefit as the system becomes more complex.

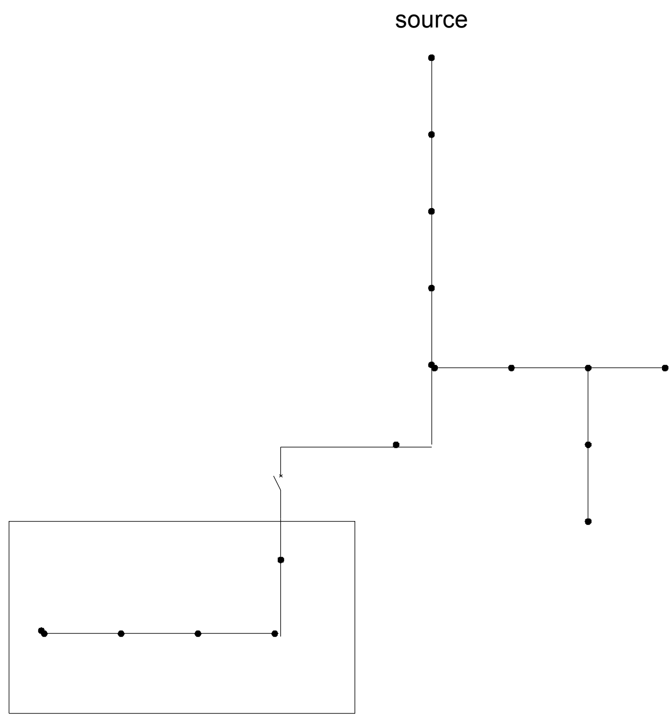

Figure 3.4 Segment Identification Scheme

3.3. Analytical Method Applied to Test System

In order to perform a reliability assessment using the analytical method, faults and the systems' response to those faults must be simulated. The analytical method includes a sequence of events that generate a set of system states for each contingency. The generalized sequence of reliability assessment considering the cases with and without DG is listed below:

1. Fault occurs on the system at component *i.*

2. All areas that are affected by fault is isolated by automatic switching. Store intermediate results for reliability indices calculation for this case: without DG and without reconfiguration.
3. Check to see if reconfiguration is possible by running power flow verifying that the source has sufficient power to supply to load
4. Restore power by reconfiguration if possible (DG not considered). Store intermediate results for reliability indices calculation for this case: without DG and with reconfiguration.
5. If restoration by reconfiguration is not possible without DG, the DG will be considered to enable restoration of power. Store intermediate results for reliability indices calculation for this case: with DG and with reconfiguration.
6. Returns to step 1 until all components in system experiences a fault.
7. Perform reliability calculations for system: without DG and without reconfiguration, without DG and with reconfiguration, and with DG (1MVA and 3MVA) and with reconfiguration.

For example, given the test system in Figure 3.5, if there is a fault on component three immediately the area between component two, which is a circuit breaker, and component nine, a relcoser, is isolated represent with solid double line. Assume there is no second feeder or reconfiguration is not a feasible option. Then, subsequently the area between component 9 and component 35, a normally open switch, must be also isolated with the dotted lines. Again since this is a radial system, hence one source of energy for

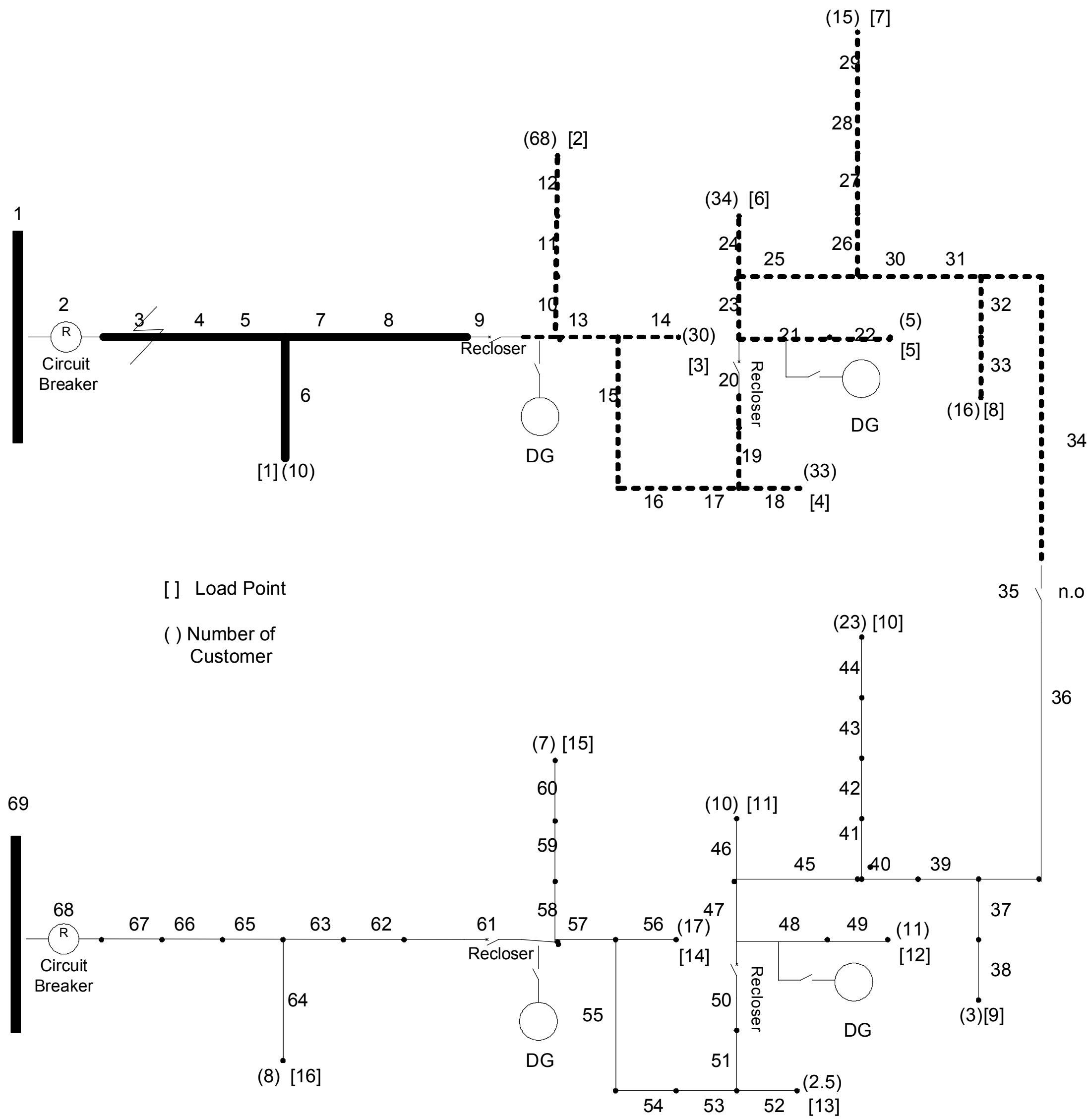

Figure 3.5 System Response to Faulted Component 3

each component, this area is also isolated leaving the entire feeder to be de-energized. It should be noted that the dotted line in Figure 3.5 represents the segment that is de-energized indirectly by a fault, while the solid double line areas represent the areas that are directly affected by a fault. Data representing the number of interrupted customers is then stored for reliability indices calculations.

Since the two radial systems are tied together by a normally open switch there is then an attempt to reconfigure the system to allow the energy source from the second system or circuit to supply power to the customers that experiences an interruption; meaning the fault is not located within their isolation region. Each load point is assigned a constant average load value taken from the load curve that is assigned to it for the Monte Carlo simulation later on. There is then a need to perform a simple power flow analysis to ensure that the line's capacity need does not exceed the amount available from the source. Data is then stored for reliability indices calculations.

Lastly, there are four distributed generator connected to the test system with a normally open switch. With these four distributed generators, it is more likely for reconfiguration that may not be possible due to line capacity limit in the without-DG case. There are two different sized DG used, 1MVA and 3MVA.

For each of the above four cases each component's failure rate is multiplied by the number of customer that would experience an interruption if that particular component was to fail. When we looked at the behavior of the system when component 3 fails, we notice that all 211 customers in the top feeder experience power interruption, therefore 211 is multiplied by the 0.025 failure rate. We then move on to component 4 and then in succession until the last component is reached. Component 67 has the identical effect on the lower feeder as shown in Figure 3.6 as component 3 has on the first system in Figure 3.5, except the failure rate is 0.079. The summation of these values divided by the total number of effected customers gives an average SAIFI value as:

$$SAIFI = \frac{\sum Total\ Number\ of\ Customer\ Interrupted}{Total\ Number\ of\ Customers\ Served} = \frac{1}{n} \cdot \sum_{i=1}^{m} \lambda_i \cdot S_i \tag{3.1}$$

where

λ_i = *failure rate of component i*

S_i = *number of customers experiencing sustained interruption due to a failure of component i*

n = *total number of customers.*

For instance, the calculation of SAIFI in actual numbers is illustrated as follow:

$$SAIFI = \frac{0.025 * 211 + ... + 0.02 * 90 + ... + 0.079 * 97.5}{292.5}$$

Similarly, when calculating the SAIDI value the number of customers effected is multiplied by the MTTR and failure rate and divide by the total number of customers that is serviced by the distribution system:

$$SAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Customers\ Served} = \frac{1}{n} \sum_{i=1}^{m} (\lambda_i \cdot D_i) \tag{3.2}$$

where

λ_i = *failure rate of component i*

D_i = *sustained interruption durations for all customers due to a failure of component i*

n = *total number of customers.*

For instance, the calculation of SAIDI in actual numbers is illustrated as follow:

$$SAIDI = \frac{0.025 * 5 * 211 + ... + 0.02 * 3 * 90 + ... + .079 * 3 * 97.5}{292.5}$$

Discussions of the system response, reconfiguration and the effect of distributed generation can be found in the next section that addresses Monte Carlo (MC) simulation. Since MC simulation represents a more complicate model, many technical details will be addressed in the next sub-section.

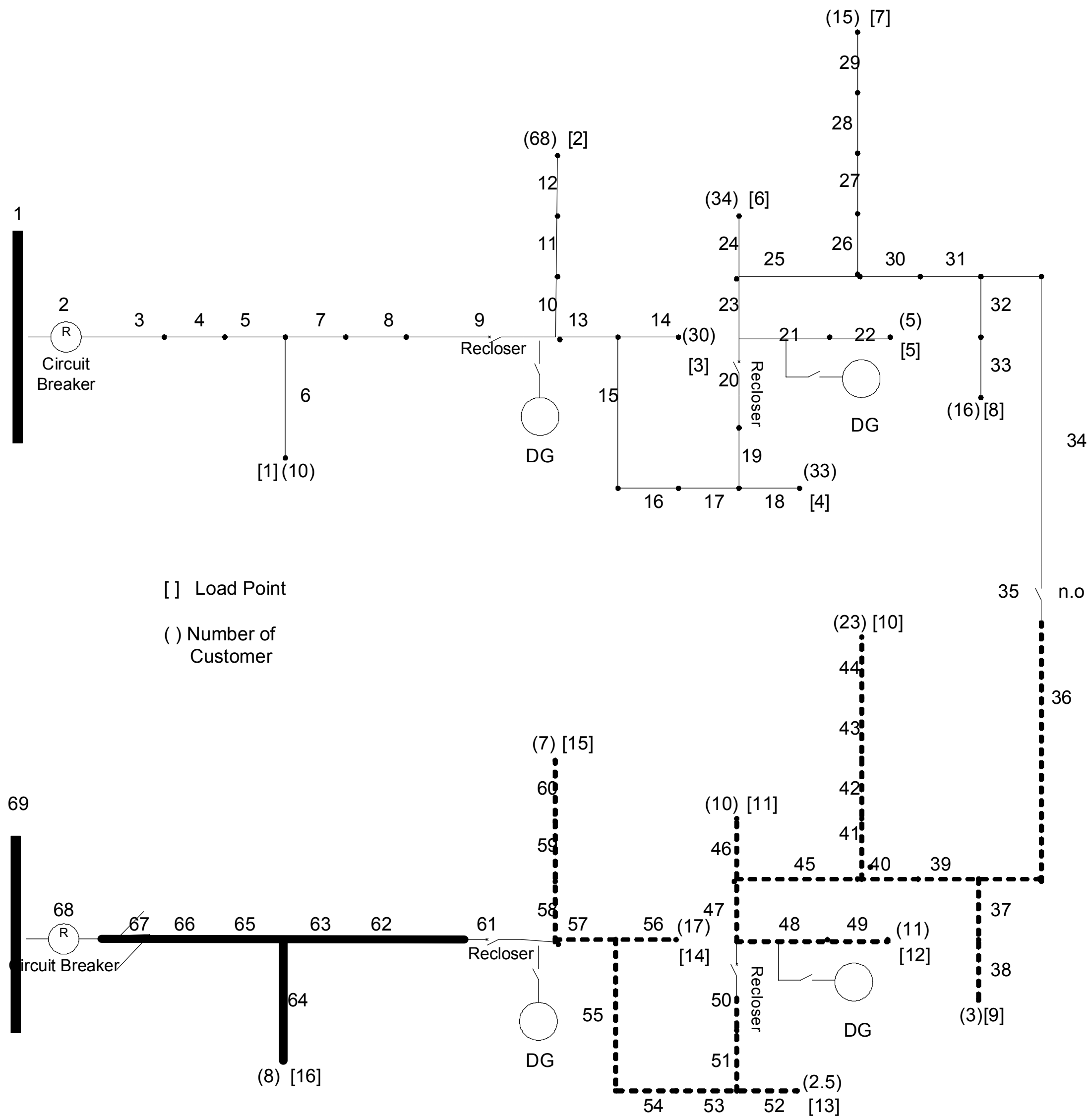

Figure 3.6 System Response to faulted component 67

3.4. Monte Carlo Simulation Applied to Test System

The analytical method definitely gives useful results, however it is a <u>constant average value</u>. In order to have more realistic results representing a statistical distribution of system reliability, it would be beneficial to show the range of possible values through probability distribution. Since the behavior of the distribution system is stochastic, we must rely on predictions in order to demonstrate the behavior. Then, we know the possibility to have a bad year with unsatisfactory reliability, the possibility to have a good year with a desired reliability, and, most likely, the possibility to have reliability indices close to an average year. Therefore, occasional bad reliability observed in the operation of a distribution company may be justified by the statistical distribution of reliability indices such that this occasional bad performance may be acceptable by regulatory authority. This is an important use to evaluate statistical distribution of distribution of reliability indices.

The Monte Carlo technique offers a way to predict behavioral patterns and to produce a probability distribution. The Monte Carlo technique is divided into two sub-techniques: sequential and non-sequential. The sequential technique models the system as it actually occur through time, while the non-sequential approach uses an arbitrary order [1]. Therefore to make the model more realistic, especially to consider operating characteristics, time-varying load, and contingence, the sequential approach is employed in this research. The generalized steps in the Monte Carlo simulation are as followed:

1. Start with the first sample year.
2. An artificial, hourly history of faults is generated.
3. Starting at time zero (first hour), identify location of the faults.

4. All areas that are affected by fault are isolated by automatic switching. Store intermediate results for reliability indices calculation for this case: without DG and without reconfiguration.
5. Check to see if reconfiguration is possible by running power flow verifying that the source has sufficient power to supply to load
6. Restore power by reconfiguration if possible (DG not considered). Store intermediate results for reliability indices calculation for this case: without DG and with reconfiguration.
7. If restoration by reconfiguration is not possible without DG, the DG will be considered to enable restoration of power. Store intermediate results for reliability indices calculation for this case: with DG and with reconfiguration.
8. Return to step two until each hour in a year has been analyzed
9. Return to step one until pre-determined stopping criteria is met (typically after thousands of iterations)
10. Perform reliability calculations for system: without DG and without reconfiguration, without DG and with reconfiguration, and with DG (1MVA and 3MVA) and with reconfiguration
11. Aggregate calculated reliability indices to produce probability distribution
12. Repeat Steps 2-11 for the following sample year till reaching a pre-determined number of sample years.

3.4.1. *Artificial Operating History*

Apparently, producing the artificial history of faults for each component is a critical requirement when performing a sequential simulation. It is necessary to predict the occurrence of contingencies and this process is driven by the reliability parameters, the failure rate and MTTR. The artificial history is a two-state model, either the component is energized and in the up state or it is de-energized and in the down state. The up state is referred to as the time to failure (TTF) and the down state is referred to as the time to repair (TTR) or time-to-switch (TTS). Since here we assume switching is automatic and instantaneous, so only TTF and TTR is considered. The transition between the two states is referred to as the failure process [14]. As previously mentioned this process is random therefore when generating there is a need to use random variables. Random values are generated between [0,1] following the exponential distribution and used to calculate TTF and TTR for each component.

$$TTF_i = -\frac{\ln(U_i)}{\lambda_i} \times 8760 \quad \text{hours} \qquad (3.3)$$

$$TTR_i = -\ln(U_i) \times MTTR_i \ \text{ hours} \qquad (3.4)$$

where λ_i =failure rate
$MTTR_i$=mean time to repair

Figure 3.7 shows the typical up down operating history of components.

There is a chance that when a region of the system is down, a fault is predicted to occur there. Of course this is not possible, the system will still be model as non-operational, however the predicted duration of the new fault is added to the current

Figure 3.7 Component up down operating history

duration time. For instance, if the system is already experiencing a fault and the duration time is predicted to be four hours and then another fault is predicted with a duration time of seven hours when the system has already been down for three hours, then duration time is extended by seven additional hours, instead of becoming operational after one more hour, the system will be down for a total of 8 hours.

3.4.2. *System Response*

After we have developed an artificial up-down history for each component, the next step is to analyze the entire year hour-by-hour identifying the location of each fault and the systems response to those faults. If we look at each hour it is our hopes and expectation that the system is operating under normal conditions, however there is the possibility that a single or even multiple components are experiencing a malfunction or there is a fault. For example, consider an extremely case that component 3, 28, and 40 might be faulted simultaneously. Figure 3.8 shows the appropriate system response. Again the dotted line represents the segment that is de-energized indirectly by a fault, and the solid double line areas represent the areas that are directly affected by a fault.

3.4.3. *Reconfiguration*

As we have seen previously, when the system responds to a contingency there are areas that are de-energized only as a consequence of the radial topology. Therefore it is beneficial and most desirable to restore power to these areas as soon as possible, even before the contingency is resolved. This approach will also improve reliability. Referring back to the test system in Figure 3.1, there is a normally open switch that is tying the two separate circuits together making it possible for the circuits to backfeed. In order for reconfiguration to be possible, first one of the two circuits from the test system must be

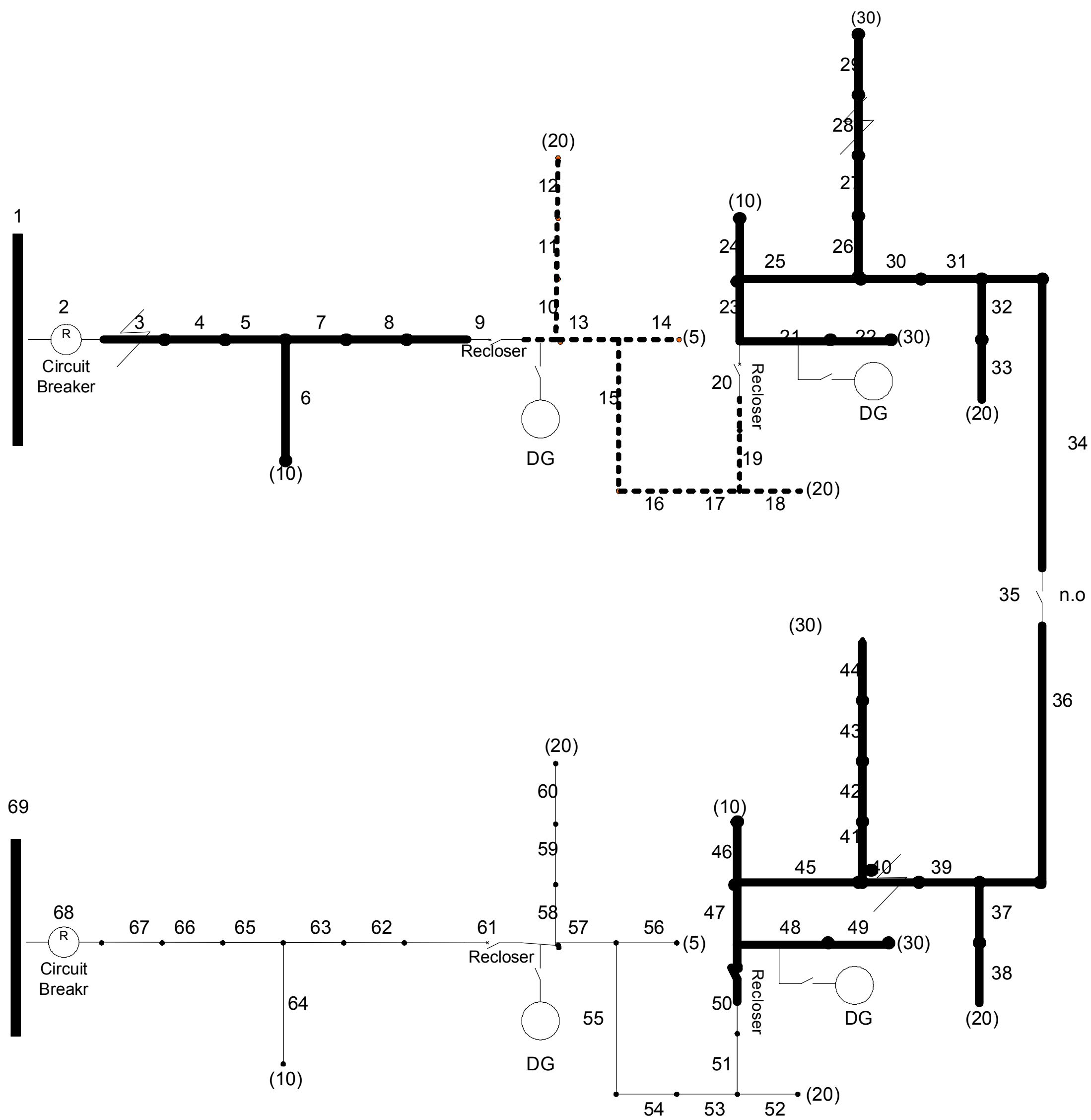

Figure 3.8 System Response to faulted components 3,28, and 40

fully operational. It then must have the capacity to support the area that is experiencing the outage. The load varies; therefore reconfiguration may be possible at one particular hour while not possible in another. This is the significant difference between the Monte Carlo simulation and analytical approach. The system response to the reconfiguration is regenerated and the data stored for reliability calculations for each hour, which will be discussed in detail later.

3.4.4. *Distributed Generation*

There is a relatively high probability that reconfiguration is not possible due to capacity issue or even location of isolated area, especially considering the increasing stress in power delivery infrastructure. The indirectly affected area may be sandwiched in between two faulted areas. Therefore DG serves a viable solution to better restore power and improve reliability. As shown in Figure 3.1, there are four DG placed in each area (the areas or regions are located between two disconnect components). The DGs are not normally connected to the circuits; it is only connected if and when there is a need. And it is assumed that they are 100% reliable, therefore the system does not experience any interconnection problems and there are always available when needed. We also assume they are automatically switched on immediately. This model did not take into consideration what type of distributed generator, whether it was fuel cells or solar powered. The distributed generators are rated at 1MVA or 3MVA as two scenarios in this study. It should be noted here that the 3MVA scenario essentially means that the distributed generators are large enough to eliminate the line capacity constraints under the back feed case. Once DG is inserted, system response is recalculated and respective data is stored for future reliability calculations.

3.4.5. *Reliability Assessment*

The way that the system responds to contingencies, reconfiguration, and the insertion of DG produces certain parameters that are necessary to perform reliability calculations. Finding the affected load due to the failure of a component and developing the up-down operating history is one of the more difficult problems when performing a Monte Carlo simulation. For different hour in a year time, the effected load points are different. The number of failures, the durations of those failures, and the duration of the up state at each of the load points are determined for a given year. We can then produce another up down operating history as in Figure 3.7 for each load point. From the load point operating history we can determine the amount of failures (failure rate) and the durations of the failures (MTTR) for each load point. Using the new parameters in Equations 3.1 and 3.2, we are able to calculate SAIFI and SAIDI values, respectively

CHAPTER 4

Results and Discussion

4.1. Analytical Simulation Results

Following the method presented in Chapter 3 Section 3, eight values were generated: four SAIFI values and four SAIDI values. The four values represent the reliability of the system for four cases: Without DG and without reconfiguration, without DG and with reconfiguration, with DG (1MVA) and with reconfiguration, and with DG (3MVA) and with reconfiguration. The MATLAB code for the algorithm can be found in the appendix. The results in Table 4.1 show a significant improvement in reliability, especially when DG is considered.

4.2. Monte Carlo Simulation Results

Following the steps discussed in Chapter 3 Section 4, one of the necessary requirements is generating an artificial operating history for each component. For example, Figure 4.1-4.3 shows the artificial operating history for component 14,51,63, respectively.

Each hour for an entire year is searched for possible contingency and system response recorded allowing for the production of an operating history for each load point in the system. Figure 4.4 shows the operating history for load point 17 without DG and without reconfiguration.

Table 4.1 Results from Analytical Approach

	SAIFI	**SAIDI**
Without DG Without reconfiguration	7.82	35.77
Without DG With reconfiguration	6.32	28.35
With DG (1MVA) With reconfiguration	5.09	23.58
With DG (3MVA) With reconfiguration	4.03	18.68

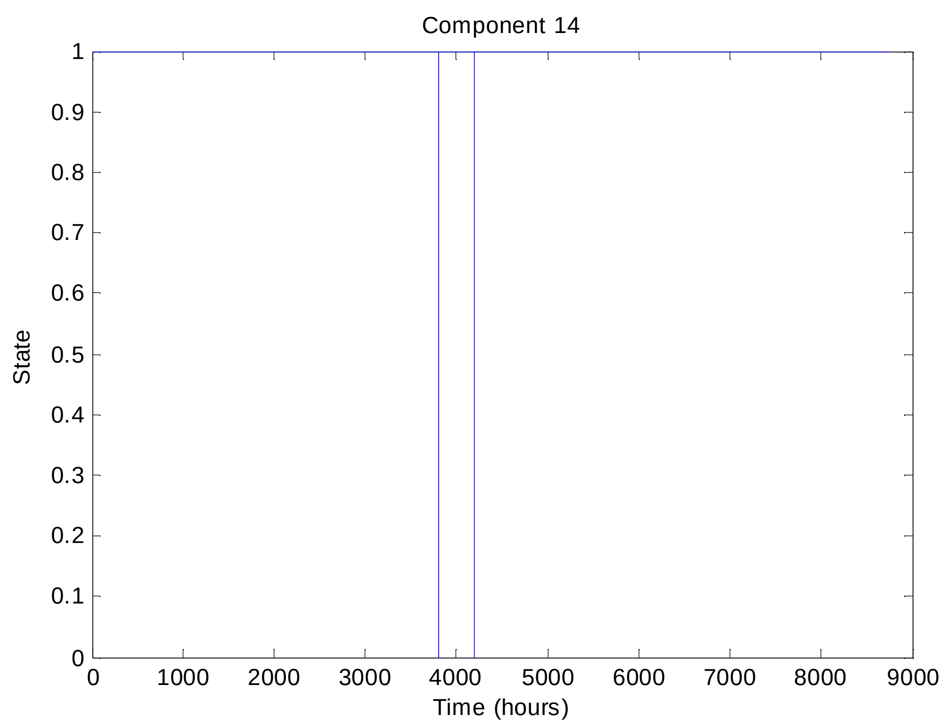

Figure 4.1 Artificial Operating History for Component 14

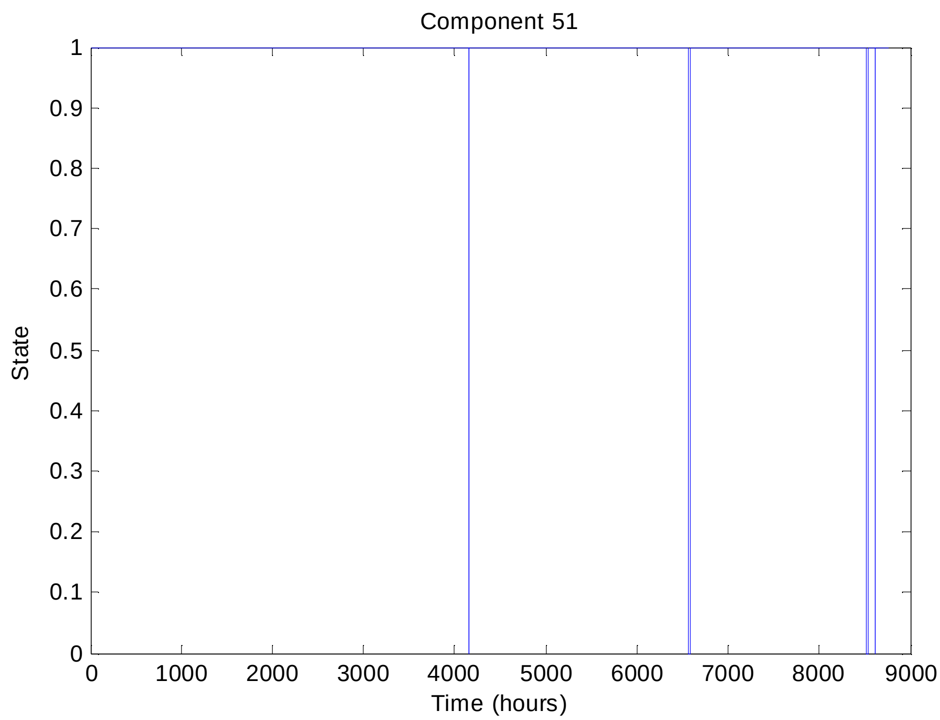

Figure 4.2 Artificial Operating History for Component 51

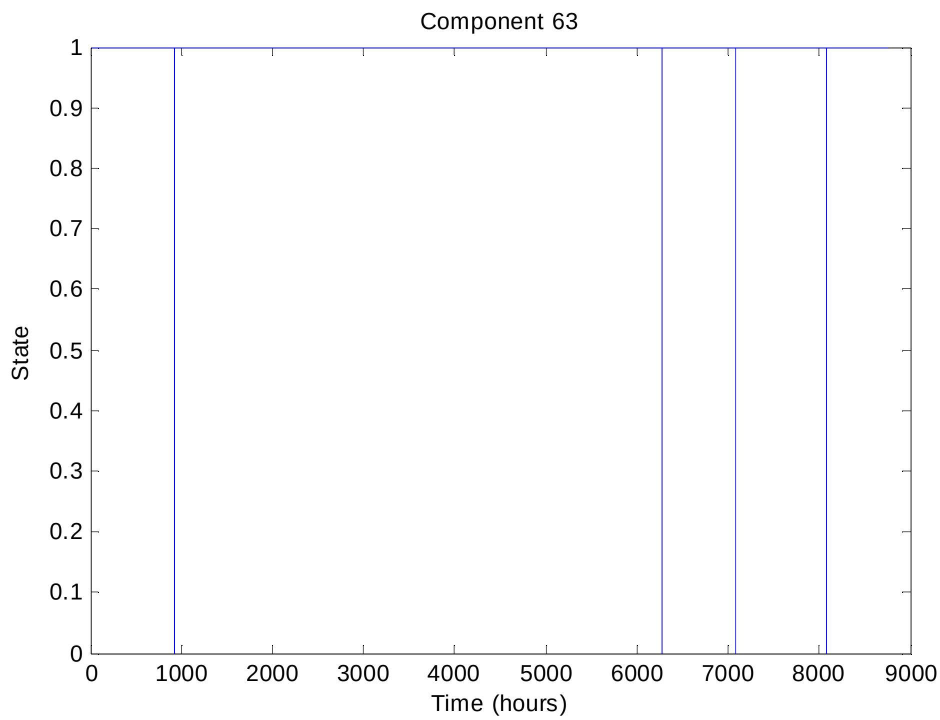

Figure 4.3 Artificial Operating History for Component 63

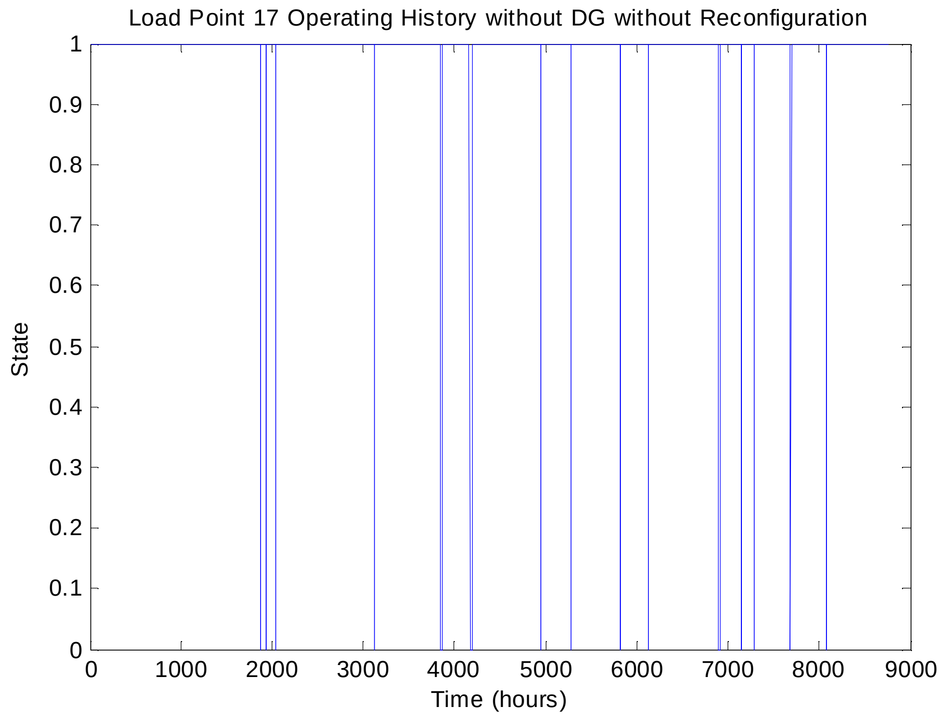

Figure 4.4 Operating History for Load Point 17

When we compare the component operating history to the load point operating history, there appear to be more transitions from state to state in the load point operating history. This is due to the fact that there is some overlapping in component failures that affect each particular load point. From the load point operating history we are able to determine a failure rate and MTTR for system reliability calculations. This process is preformed for a total of 1000 Monte Carlo sample years producing eight probability distributions: four for SAIFI and four for SAIDI shown in Figures 4.5-4.12.

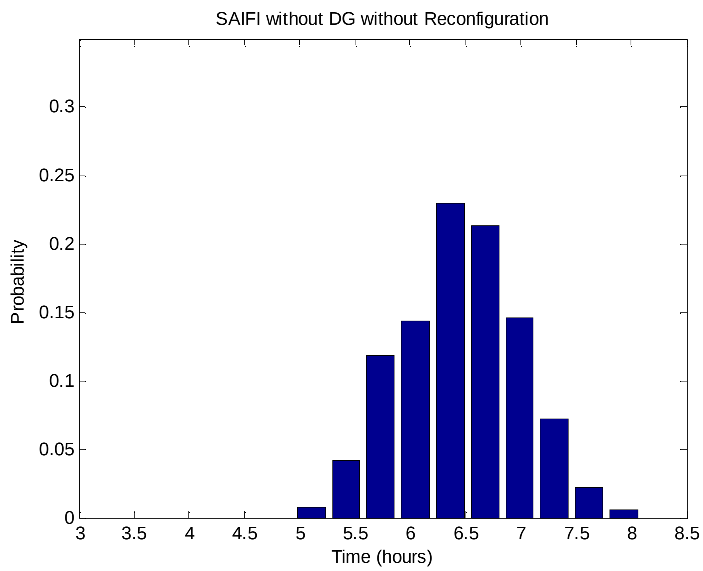

Figure 4.5 SAIFI Probability Distribution for System without DG without Reconfiguration

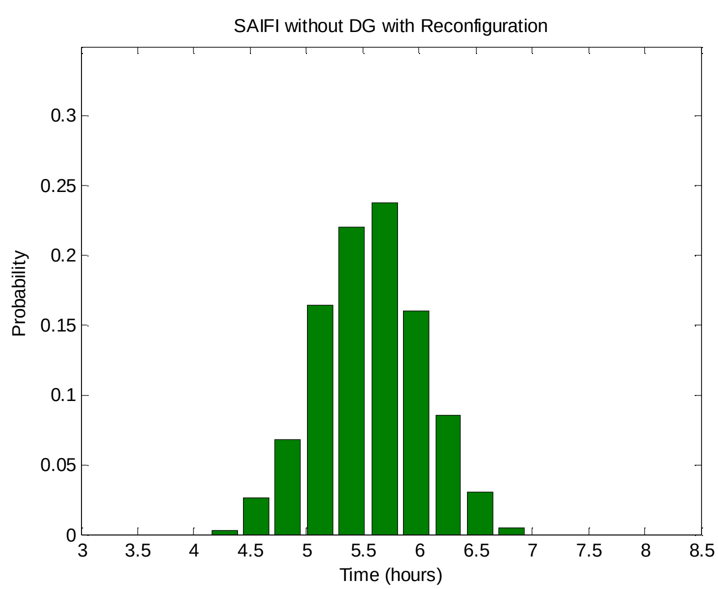

Figure 4.6 SAIFI Probability Distribution for System without DG with Reconfiguration

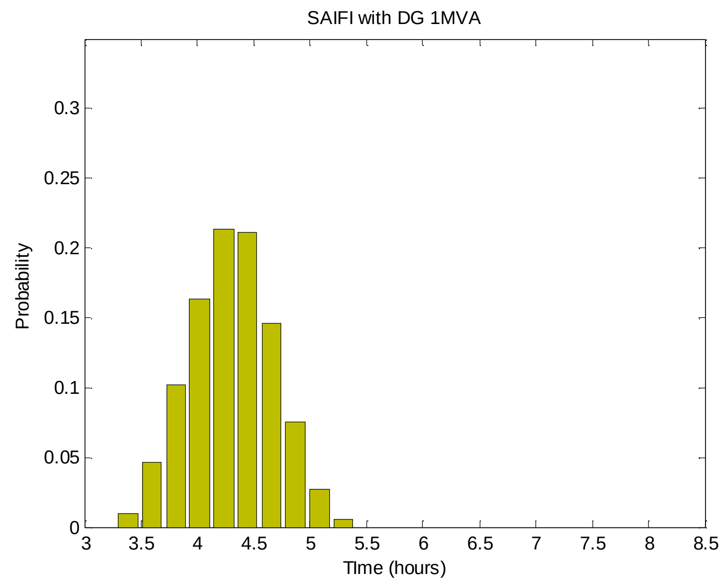

Figure 4.7 SAIFI Probability Distribution for System with DG 1MVA

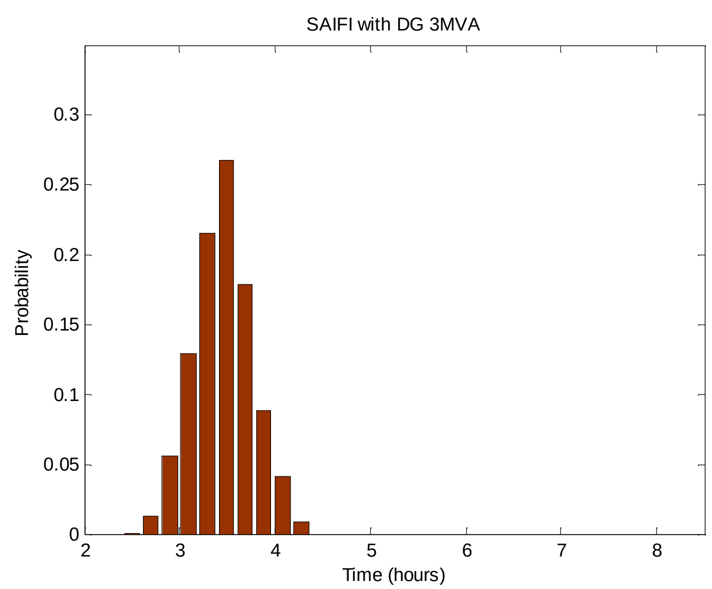

Figure 4.8 SAIFI Probability Distribution for System with DG 3MVA

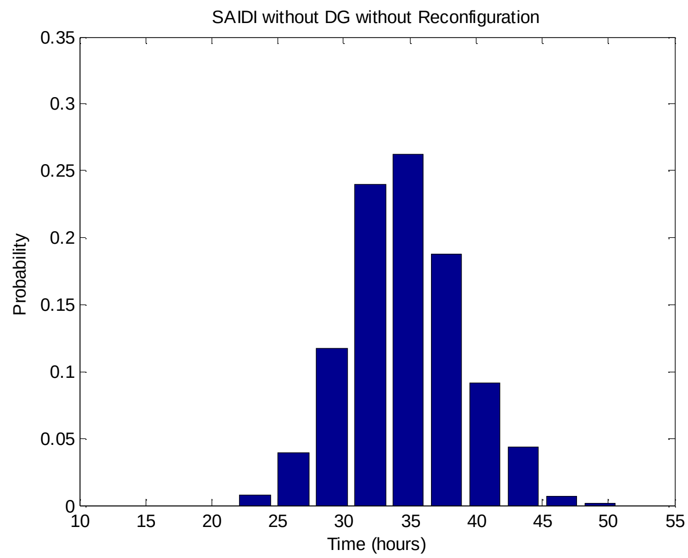

Figure 4.9 SAIDI Probability Distribution for System without DG without Reconfiguration

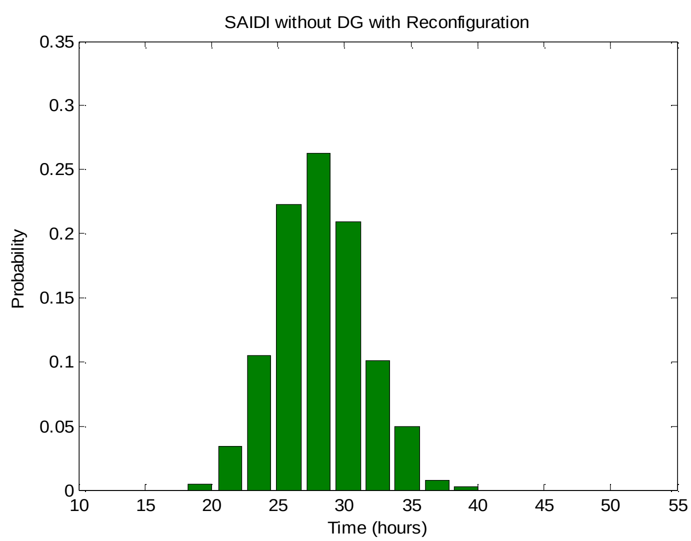

Figure 4.10 SAIDI Probability Distribution for System without DG with Reconfiguration

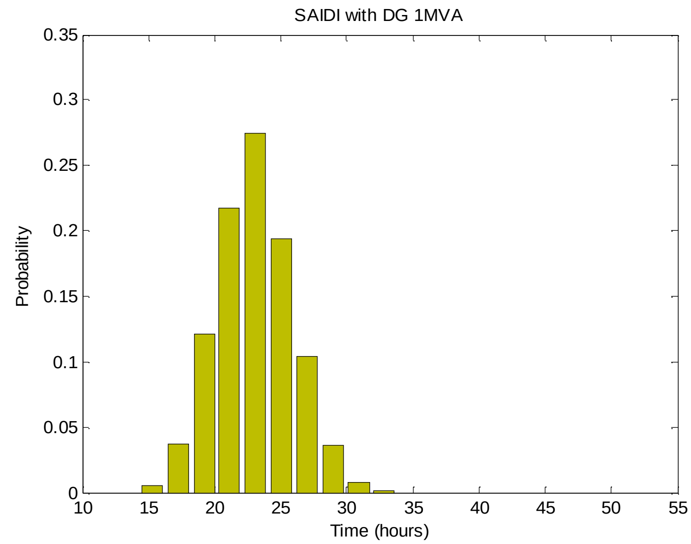

Figure 4.11 SAIDI Probability Distribution for System with DG 1MVA

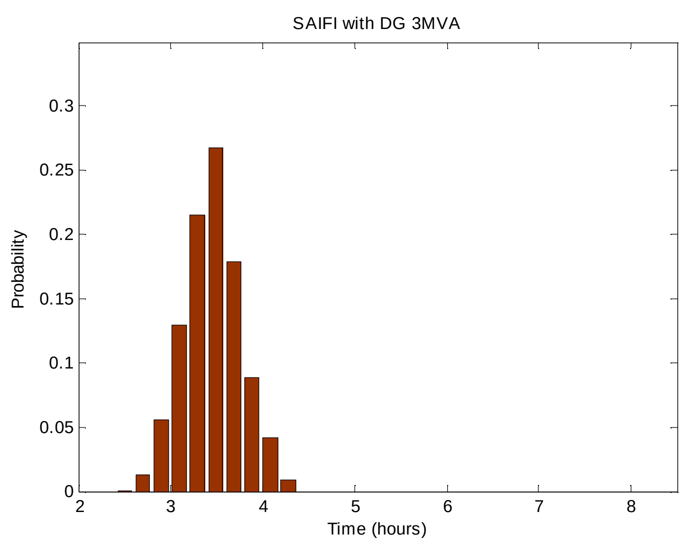

Figure 4.12 SAIDI Probability Distribution for System with DG 3MVA

4.3. Analytical Method and Monte Carlo Method Comparison

Table 4.2 compares the mean values of SAIFI and SAIDI results from the Analytical Approach and the Monte Carlo simulation. It is clearly shown that with either approach the interconnection of DG can improve the system reliability indices. And certainly, with larger distributed generators, the reliability will be further improved.

Again, MC simulation can show statistical distribution of SAIFI and SAIDI, which can be found in Figures 4.5 to 4.12.

Table 4.2 Analytical and Monte Carlo Results

	Analytical	Monte Carlo
SAIFI without DG without Reconfiguration	7.82	6.50
SAIFI without DG with Reconfiguration	6.32	5.60
SAIFI with DG 1MVA	5.09	4.33
SAIFI with DG 3MVA	4.03	3.45
SAIDI without DG without Reconfiguration	35.77	34.98
SAIDI without DG with Reconfiguration	28.35	28.42
SAIDI with DG 1MVA	23.58	23.42
SAIDI with DG 3MVA	18.68	18.36

CHAPTER 5

Conclusions and Recommendations

5.1. Conclusion

This research seeks to model the impact of distributed generation to distribution system reliability. Since utility-connected distributed generation is typically installed close to the consumers, it can reduce the current at the main feeder. Consequently, it increases the chance that a stressed feeder can be reconfigured under a fault at a neighboring feeder. As a comparison, it may be impossible to reconfigure feeder connection because reconfiguration will lead to line overflow without distributed generators to supply part of the load.

The reliability assessment in this work is carried out with analytical approach and sequential Monte Carlo simulation. The analytical approach presents the reliability measures like SAIFI and SAIDI during the course of an average year. Hence, the mean values of SAIFI and SAIDI for distribution systems with or without distributed generation are obtained. However, sequential Monte Carlo simulation can give the probabilistic distribution of SAIFI and SAIDI based on a large sample of random failures of system components. Test results from a test system modified from the IEEE 34-bus system are presented based on the analytical approach and the Monte Carlo simulation. It is shown that installation of distributed generators can improve the distribution system reliability considerably.

5.2. Future Work

Future work may lie in a deeper analysis of impact of reliability with different size of DGs at different locations. Further, when different types of DGs are considered, the results may be different. For instance, the photovoltaics have an output patterns affected by sun light, and the distributed wind generators have an output patterns greatly affected by the wind. Hence, the time of possible component failure will have an impact on whether reconfiguration with DG is possible or not.

Another important extension of this work is to identify possible approaches to identify the optimal location of DGs considering reliability measures. If we consider system reliability indices, perhaps with a weighted average of multiple indices like SAIFI and SAIDI, as the objective function to minimize, this will be non-linear and non-continuous optimization problem with respect to DG size and location. If some heuristic rules such as sensitivity of SAIFI and SAIDI with DG sizes and location can be identified from research works similar to this one, it can significantly simplify the optimization model. Therefore, it will be easier to combine the reliability measures as part of a multi-objective optimization considering reliability, power losses, environmental impact, and so on.

Lastly, as utilities customers' usage of sensitive electronics increase, the slightest disruption of power may have catastrophic affects. Therefore, it will be beneficial to study what role momentary interruption play in the overall reliability of the system.

LIST OF REFERENCES

LIST OF REFERENCES

1. Brown, R.E., *Electric Power Distribution Reliability*. 2002.
2. R.E.Brown and J.R. Ochoa, *Distribution System Reliability: Default Data and Model Validation.* IEEE Transactions on Power System, 1998. **13**(2).
3. Balijepalli, N., S.S. Venkata, and R.D. Christie, *Modeling and Analysis of Distribution Reliabiliyt Indices.* IEEE Transactions on Power Delivery, 2004. **19**(4).
4. Brown, R.E. and J.J. Burke, *Managing the Risk of Performance Based Rates.*
5. Committee, T.a.D., *1366 IEEE Guide for Electric Power Distribution Reliability Indices*. 2004: The IEEE, Inc.
6. Wang, Z., R. Shokooh, and J. Qui, *An Efficient Algorithm for Assessing Reliability Indexes of General Distribution Systems.* IEEE Transactions on Power System, 2002. **17**(3).
7. Brown, R.E., *Reliability Benefits of Distributed Generations on Heavily Loaded Feeders.* 2007.
8. Hegazy, Y.G., M.M.A. Salaama, and A.Y. Chikhani, *Adequacy Assessment of Distributed Generation Systems Using Monte Carlo Simulation.* IEEE Transactions on Power System, 2003. **18**(1).
9. Zhu, D., *Power System Reliability Analysis with Distributed Generators* 2003, Virginia Polytechnic Institute and State University.
10. Brown, R.E., *Modeling the Reliability Impact of Distributed Generation.* ABB Consulting, 2002.
11. Warren, C.A. and R. Saint, *IEEE Reliability Indices Standards*, in *IEEE Industry Applications Magazine*. 2005.
12. Wang, P. and R. Billinton, *Time Sequential Distribution System Reliability Worth Analysis Considering Time Varying Load and Cost Models.* IEEE Transactions on Power Delivery, 1999. **14**(3).
13. R.E.Brown, et al., *Distribution System Reliability Assessment Using Hierarchical Markov Modeling.* IEEE Transactions on Power Delivery, 1996. **11**(4).
14. Billinton, R. and P. Wang, *Teaching Distribution System Reliability Evaluation using Monte Carlo Simulation.* IEEE Transactions on Power Systems, 1999. **14**(2).
15. Sankarakrishnan, A. and R. Billinton, *Sequential Monte Carlo Simulation for Composite Power System Reliability Analysis with TIme Varying Loads.* IEEE Transactions on Power Systems, 1995. **10**(3).
16. Carpaneto, E. and G. Chicco, *Evaluation of the Probability Density Functions of Distribution System Reliability Indices with a Characteristic Functions-Based Approach.* Ieee Transactions on Power Systems, 2004. **19**(2).
17. Asgarpoor, S. and M.J. Mathine, *Reliability Evaluation of Distribution Sytems with Non-Exponential Down Times.* IEEE Transactions on Power Systems, 1997. **12**(2).
18. Silva, A.M.L.d., et al., *Analytical and Monte Carlo Approaches to Evaluate Probability Distributions of Interruption Duration.* IEEE Transactions on Power Systems, 2005. **20**(3).

19. Billinton, R. and W. Wangdee, *Impact of Utilizing a Sequential and Non-Sequential Simulation Techniques in Bulk-Electric-System Reliability Assessment.* IEE Proc.-Gener. Transm. Distrib., 2005. **152**(5).
20. Brown, R.E., G. Frimpong, and H.L. Willis, *Failure Rate Modeling Using Equipment Inspection Data.* IEEE Transactions on Power Systems, 2004. **19**(2).
21. Zhu, D., et al., *Impact of DG Placement on Reliability and Efficiency with Time-Varying Loads.* IEEE transactions on Power Systems, 2006. **21**(1).
22. Dugan, R.C. and S.K. Price, *Including Distributed Resources in Distribution Planning.* 2004.
23. *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, in *STD 1547*, IEEE, Editor. 2003.
24. Edwards, F.V., et al., *Dynamics of Distribution Networks with Distributed Generations.* IEEE 2000.
25. Dugan, R.C., T.S. Key, and G.J. Ball, *On Standards for Interconnecting Distributed Resources.*
26. Marei, M.I., E.F. El-Saadany, and M.M.A. Salaam, *A Novel Control Algorithm for the DG Interface to Mitigate Power Quality Problems.* IEEE Transactions on Power Delivery, 2004. **19**(3).
27. Kashem, M.A. and G. Ledwich, *Distributed Generation as Voltage Support for Single Wire Earth Return Systems.* IEEE Transactions on Power Delivery, 2004. **19**(3).
28. Dugan, R., *Computing Incremental Capacity Provided By Distributed Resources For Distribution Planning.* 2007.
29. Baker, P.P. and R.W. deMello, *Determining the Impact of Distributed Generation of Power Systems: Part 1 - Radial Distribution Systems.* Power Technologies, INc, 2000.
30. Fangxing Li, Richard E. Brown, and Lavelle A.A. Freeman, *A Linear Contribution Factor Model and its Applications in Monte Carlo Simulation and Sensitivity Analysis*, IEEE Trans. on Power Systems, vol. 18, no. 3, pp1213-1215, August 2003.
31. Fangxing Li, *Distributed Processing for Reliability Assessment and Reliability-Based Network Reconfiguration with Simulated Annealing, I*EEE Transactions on Power Systems, vol. 20, no. 1, pp. 230-238, February 2005.
32. IEEE/PES Working Group on System Design, *A survey of distribution reliability measurement practices in the US*, IEEE Trans. on Power Delivery, Vol. 14, No.1, pp250-257, January 1995.

APPENDIX

Main Program

The MATLAB code below is part of entire MATLAB tool developed during this research work. It is printed here to illustrate the main procedure to produce the results presented in this paper. Other unlisted code includes topological search, artificial history generator, and load point failures and failure duration counter.

This is the initial input of the distribution system, showing the parent/child relationship for each component.

```
Parent=[0;1;2;3;4;
    5;5;7;8;9;
    10;11;10;13;13;
    15;16;17;17;19;
    20;21;20;23;23;
    25;26;27;28;26;
    30;31;32;32;34;
    35;36;37;37;39;
    40;41;42;43;40;
    45;45;47;48;47;
    50;51;51;53;54;
    55;55;57;58;59;
    57;61;62;63;63;
    65;66;67;68]';
```

For each load point the number of customers are assigned

```
customer=[0;0;0;0;0;
    10;0;0;0;0;
    0;68;0;30;0;
    0;0;33;0;0;
    0;5;0;34;0;
    0;0;0;15;0;
    0;0;16;0;0;
```

```
    0;0;3;0;0;
    0;0;0;23;0;
    10;0;0;11;0;
    0;2.5;0;0;0;
    17;0;0;0;7;
    0;0;0;8;0;
    0;0;0;0]';
```

Calculates the total number of customer in the entire system

```
t_cust=0;
for n=1:length(customer)
    t_cust=t_cust +customer(n);
end
ncomp=length(Parent);
```

This is the reliability indices, MTTR and FR

```
MTTR=[0;0;5;6;2;
    8;7;6;0;2;
    4;4;5;3;6;
    4;8;7;2;0;
    6;6;4;1;2;
    4;2;3;6;5;
    3;4;5;2;0;
    4;6;8;6;3;
    7;5;2;6;3;
    4;2;3;4;0;
    6;3;7;4;2;
    5;6;3;4;6;
    0;4;2;1;6;
    5;3;0;0]';

fr=[0;0.0;0.015;0.06;0.09;
    0.018;0.017;0.036;0;0.02;
    0.014;0.014;0.035;0.03;0.06;
    0.09;0.08;0.027;0.02;0.0;
    0.026;0.06;0.07;0.011;0.02;
    0.034;0.012; 0.03;0.016;0.025;
    0.03;0.04;0.05;0.032;0.0;
    0.04;0.036;0.038;0.056;0.063;
    0.017;0.025;0.032;0.016;0.033;
    0.057;0.042;0.03;0.014;0.0;
    0.036;0.022;0.025;0.036;0.033;
    0.024;0.006;0.004;0.024;0.032;
```

```
    0.0;0.006;0.045;0.063;0.054;
    0.088;0.079;0.0;0]'; % no big failure rate of 0.27*100=27
fr=fr*100;
```

The time in hours of how long the simulation will run.

```
time=8760;
```

Initialize vectors

```
Child=zeros(length(Parent),4);
flagged=zeros(1,length(Parent));
```

Generates a list of Children from the Parent input

```
for i=1:length(Parent)
    v=Parent(i);
    s=find(Parent==v);
    while(v==0)
        v=v+1;
    end

    if length(s)>=2
        for m=1:length(s)
        j=s(m);
        Child(v,m)=j;
        end
    elseif length(s)<s
            Child(v)=s;
    end
end
```

Generates Number of Children of each components

```
NumChild=zeros(1,length(Child));
for n=1:length(Child)
    y=Child(n,:);
    f=find(y>0);
    a=length(f);
    NumChild(n)=a;
end

%This portion identifies the location of the breakers/sectionalizers/fuses
breaker=zeros(1,length(Parent));
```

```
breaker(2)=1;
breaker(9)=1;
breaker(20)=1;
breaker(50)=1;
breaker(61)=1;
breaker(68)=1;
```

This portion identifies the location of the sources and the peak loading ratings for each source

```
source=zeros(1,length(Parent));
source(1)=1;
source(69)=1;
max_rat(1)=1800;
max_rat(69)=1000;
```

This portion identifies the location of the normal open switches

```
NO=zeros(1,length(Parent));
NO(1)=1;
NO(end)=1;
NO(35)=1;
```

Identifies the location of the load points

```
F1=[0;0;0;0;0;
    1;0;0;0;0;
    0;1;0;1;0;
    0;0;1;0;0;
    0;1;0;1;0;
    0;0;0;1;0;
    0;0;1;0;0;
    0;0;1;0;0;
    0;0;0;1;0;
    1;0;0;1;0;
    0;1;0;0;0;
    1;0;0;0;1;
    0;0;0;1;0;
    0;0;0;0]';

LF=find(F1==1);
```

Takes load 4 different load curves from excel and scale them to generate additional load curves for the each load point in the system

```
[load1] = xlsread('C:\Documents and Settings\nura\My
Documents\Research\Load_4Areas','c2:f8761');
load1(:,1)=load1(:,1)*.1;
```

Using scaled loads to generate twelve additional loads for each load point

```
for t=1:length(load1(1,:))
   num(:,t)=load1(:,t)/2;
end
round(num);
load=[load1 num];

for t=1:length(load1(1,:))
   num1(:,t)=load1(:,t)/3;
end
round(num1);
load=[load1 num num1];

for t=1:length(load1(1,:))
   num2(:,t)=load1(:,t)/4;
end
round(num2);
load=[load1 num num1 num2];

load(1:length(LF));

for s=1:length(load(1,:))
   t(s)=mean(load(:,s));
end


for s=1:length(load(1,:))
   y(s)=mean(load(:,s));
end

avg=t;
peak=max(load(:,:));
```

Find the average and peak value for each load point

```
for s=1:length(load(1,:))
   avg(s)=mean(load(:,s));
```

```
end
avg;
peak=max(load(:,:));

%Plots the load point
figure(1)
plot([1:time],load)
```

Assigns each load curve to a load point

```
for yy=1:length(load(:,1))
   for pp=1:length(LF)
      F(yy,LF(pp))=load(yy,pp);
   end
end
for ii=1:length(load(:,1))
   for uu=length(F(1,:)):length(Parent)
      F(ii,uu)=0;
   end
end
```

Calculates the current rating from n.o. switch to first source

```
for yy=1:length(load(:,1))
  m=find(NO);
  m=m(2:end-1);
   for h=m:-1:2
      m=m-1;
      F(yy,m)=F(yy,h)+F(yy,m);
   end
end
G=F;
```

Calculates the current rating from n.o. switch to second source

```
for yy=1:length(load(:,1))
  m=find(NO);
  m=m(2:end-1);
  q=m;
   for t=q:length(Parent)-1
      q=q+1;
```

```
        F(yy,q)=F(yy,t)+F(yy,q);
    end
end
G=F;
G=round(G);
M=G;
```

Take average values of load curve for each load point Calculates the current ratings for the system.

```
G=[];
m=find(NO);
m=m(2:end-1);
q=m;
qq=m;
```

Assigns each load curve to a load point

```
    for pp=1:length(LF)
        F1(LF(pp))=avg(pp);
    end


for ii=1:length(load(:,1))
    for uu=length(F(1,:)):length(Parent)
        F(ii,uu)=0;
    end
end
```

Identifies location of breaker and normal open switch(es)

```
n=find(NO);
n=n(2:end-1);
first=n;
second=n;
breaker2=find(breaker);
```

Calculates the current rating from n.o. switch to first source

```
   m=find(NO);
```

```
   m=m(2:end-1);
    for h=m:-1:2
        m=m-1;
        F1(m)=F1(h)+F1(m);
    end

G=F1;
```

Calculates the current rating from n.o. switch to second source

```
   m=find(NO);
   m=m(2:end-1);
   q=m;
    for t=q:length(Parent)-2
        q=q+1;
        F1(q)=F1(t)+F1(q);
    end
G=F1;
```

Analytical Simulation

```
for zz=1:1
for h=1:length(Parent)
    flagged=zeros(1,length(Parent));
    fault=h;
```

Isolates area effected by fault

```
    [flagged]=isolate1(breaker,breaker2,fault,flagged,n,NO,customer);
```

Isolates secondary area effected by fault

```
    [flagged breaker1]=isolate_sec1(flagged,breaker,qq,Parent);
    eff=find(flagged>=1);
    if eff>=1
        eff_cust(h)=sum(customer(eff(1):eff(end)));
    else
        eff_cust(h)=0;
    end
```

Start the reconfiguration process

```
[flagged]=reconfig2(flagged,max_rat,breaker1,qq,G,M,zz);
eff=find(flagged>=1);
if eff>=1
    eff_cust_reconfig(h)=sum(customer(eff(1):eff(end)));
else
    eff_cust_reconfig(h)=0;
```

```
end
```

Insert DG

```
[flagged]=DG(flagged,breaker1,G,qq,zz);
eff=find(flagged>=1);
if eff>=1
   eff_cust_DG(h)=sum(customer(eff(1):eff(end)));
else
   eff_cust_DG(h)=0;
end
end
end
```

Calculates SAIFI/SAIDI

```
for g=1:length(Parent)-1
SAIFI_A(g)=fr(g)*eff_cust(g);
SAIDI_A(g)=fr(g)*MTTR(g)*eff_cust(g);
% SAIDI_A(g)=fr(g)*MTTR(g);
end
```

Calculates SAIFI/SAIDI for reconfig

```
for g=1:length(Parent)-1
SAIFI_reconfig_A(g)=fr(g)*eff_cust_reconfig(g);
SAIDI_reconfig_A(g)=fr(g)*MTTR(g)*eff_cust_reconfig(g);
end
```

Calculates SAIFI/SAIDI for DG

```
for g=1:length(Parent)-1
SAIFI_A_DG(g)=fr(g)*eff_cust_DG(g);
SAIDI_A_DG(g)=fr(g)*MTTR(g)*eff_cust_DG(g);
end
```

Line flow for Monte Carlo

```
G=M;

hm=0;
for tt=1:1


   hm=hm+1;
```

Runs Monte Carlo program to identify possible faults for all components

```
   [comp]=failure9(fr,MTTR);
```

```
num=0;
for zz=1:time

flagged=zeros(1,length(Parent));

   num=num+1;
```

Identifies location of fault

```
fault=find(comp(:,zz)==0)';
```

Isolates area effected by fault

```
[flagged]=isolate1(breaker,breaker2,fault,flagged,n,NO,customer);
```

Isolates secondary area effected by fault

```
[flagged breaker1]=isolate_sec1(flagged,breaker,qq,Parent);
```

Develops Load Point yearly interruption activity

```
for aa=1:length(LF)
   if flagged(LF(aa))>=1
      LP(aa,zz)=0;
   else
      LP(aa,zz)=1;
   end
end
```

Start the reconfiguration process

```
[flagged]=reconfig2(flagged,max_rat,breaker1,qq,G,M,zz);
```

Develops Load Point yearly interruption activity

```
for aa=1:length(LF)
   if flagged(LF(aa))>=1
      LP_reconfig(aa,zz)=0;
   else
      LP_reconfig(aa,zz)=1;
   end
end
```

Insert DG

```
[flagged]=DG(flagged,breaker1,G,qq,zz);
```

Develops Load Point yearly interruption activity

```
   for aa=1:length(LF)
      if flagged(LF(aa))>=1
         LP_DG(aa,zz)=0;
      else
         LP_DG(aa,zz)=1;
      end
   end
   end
```

Plots the up down graph for each load point

```
%     for x=1:length(LF)
%        figure(x+1)
%        plot([1:time],LP(x,:))
%     end
%     for x=1:length(LF)
%        figure(x+1)
%        plot([1:time],LP_reconfig(x,:))
%     end
%     for x=1:length(LF)
%        figure(x+17)
%        plot([1:time],LP_DG(x,:))
%     end
```

Identifies how many customers are effected for each point

```
   cust_eff=[10; 68; 30; 33; 5;
        34;15;16;3;23;
        10;11;2.5;17;7;
        8];
```

Determines how many failures, and how long each failure is experienced by each load point

```
   [R Q]=fail10(LP)
   [R_reconfig Q_reconfig]=fail10(LP_reconfig)
   [R_DG Q_DG]=fail10(LP_DG)
```

Calculates the SAIFI/SAIDI

```
   SAIFI1(tt)=R*cust_eff/sum(cust_eff)/10;
   SAIFI_reconfig1(tt)=R_reconfig*cust_eff/sum(cust_eff)/10;
   SAIFI_DG1(tt)=R_DG*cust_eff/sum(cust_eff)/10;
   SAIDI1(tt)=Q*cust_eff/sum(cust_eff)/10;
   SAIDI_reconfig1(tt)= Q_reconfig*cust_eff/sum(cust_eff)/10;
   SAIDI_DG1(tt)=Q_DG*cust_eff/sum(cust_eff)/10;

end
```

```
vv=1;
hm
num

disp('Analytical')
SAIFI_A1=sum(SAIFI_A)/t_cust/10
SAIFI_reconfig_A1=sum(SAIFI_reconfig_A)/t_cust/10
SAIFI_A1_DG=sum(SAIFI_A_DG)/t_cust/10

SAIDI_A1=sum(SAIDI_A)/t_cust/10
SAIDI_reconfig_A1=sum(SAIDI_reconfig_A)/t_cust/10
SAIDI_A1_DG=sum(SAIDI_A_DG)/t_cust/10


disp('Monte Carlo')

results=[std(SAIFI1) var(SAIFI1) mean(SAIFI1);
    std(SAIFI_reconfig1) var(SAIFI_reconfig1) mean(SAIFI_reconfig1);
    std(SAIFI_DG1) var(SAIFI_DG1) mean(SAIFI_DG1);
    std(SAIDI1) var(SAIDI1) mean(SAIDI1);
    std(SAIDI_reconfig1) var(SAIDI_reconfig1) mean(SAIDI_reconfig1);
    std(SAIDI_DG1) var(SAIDI_DG1) mean(SAIDI_DG1)]'

 fprintf(1,'SAIFI std deviation is %6.2f, variance is %6.2f, and mean value is %6.2f\n',
results);
peak
avg
```

Creates a histogram for SAIFI/SAIDI

```
figure(vv+1)
[n xout]=hist(SAIFI1);
bar(xout,n/hm)

figure(vv+2)
[n xout]=hist(SAIFI_reconfig1);
bar(xout,n/hm)

figure(vv+3)
[n xout]=hist(SAIFI_DG1);
bar(xout,n/hm)

figure(vv+4)
[n xout]=hist(SAIDI1);
```

```
bar(xout,n/hm)

figure(vv+5)
[n xout]=hist(SAIDI_reconfig1);
bar(xout,n/hm)

figure(vv+6)
[n xout]=hist(SAIDI_DG1);
bar(xout,n/hm)
```

Vita

Nura Sabir began studying engineering in 2000. While she worked towards here bachelors degree she completed a co-op with National Aeronautical Space Administration, Goddard Space Flight Center in Greenbelt Maryland and an internship with General Electric in Greenville South Carolina. She received her Bachelors in Electrical Engineering at Tuskegee University located in Tuskegee Alabama in 2005. Before she came to The University of Tennessee, Knoxville to pursue her Masters Degree, she was employed as a Technical Reprehensive by Space and Naval Warfare System Center in San Diego California. During her studies at The University of Tennessee she has completed an internship with Center of Naval Analysis in Alexandria Virginia. Prior to graduation she was extend to offers, Alcoa Inc and Engineering Planning and Management (EPM), Inc. God willing, she plans to accept with EPM and begin work in the fall.